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## RAPID LASER HEATING OF METALS UNDER CONSTANT UNIAXIAL STRESS

Keith G. Gilbert  
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TECHNICAL REPORT NO. AFWL-TR-72-12

May 1972

AIR FORCE WEAPONS LABORATORY

Air Force Systems Command

Kirtland Air Force Base

New Mexico

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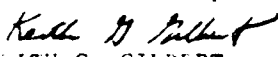
FORWORD


This research was performed under Program Element 63605F, Project 317J, Task II.


The inclusive dates of research were 1 October 1970 to 25 November 1971. The report was submitted 15 March 1972 by the Air Force Weapons Laboratory Project Officer, Major Keith Gilbert (LRE).

The authors wish to thank Captain Bill Laughlin for his many valuable comments. Gratitude is also extended to Bob Belland and Ron Smith, who operated the tensile unit during these experiments.

This report has been reviewed and is approved.

  
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ABSTRACT

(Distribution Limitation Statement B)

This experimental program examined the strength-temperature relationship of four metals subjected to rapid laser heating. The materials studied were 6Al4V annealed titanium alloy, 304 annealed stainless steel, AZ-31B hard rolled magnesium, and 2024 age-hardened aluminum.

A 200-watt CO<sub>2</sub> laser heated the metal samples while they were being held under a constant uniaxial tensile stress. The heating times ranged from 0.1 second to several seconds while the heating rates varied from 0.25 to 1.9 times the metals' melting temperature in degrees centigrade per second. Sample yield was defined as a 0.2 percent offset in excess of the laser-induced thermal expansion.

In general the samples heated rapidly by the laser show higher yield temperatures than their conventional long soak counterparts, an effect caused by inertial mechanical and metallurgical properties.

Magnesium AZ-31B yield temperatures are 75 to 110°C higher than long soak specimens for loads from 10 to 50 percent of room temperature yield.

Stainless steel 304 yield temperature shows a strong dependence on heating rate. Under a uniaxial stress of 25 percent of the room temperature yield stress, the yield temperatures for heating rates of zero (long soak), 340°C/sec and 960°C/sec are 750°C, 920°C, and 1100°C, respectively.

Titanium 6Al4V yield temperature has very little dependence on heating rate. Yield data on 2024 aluminum under rapid laser heating agrees well with that from rapid electrical resistance heating. Both yield temperatures lie 50 to 100°C above the long soak data.

The residual strength of samples irradiated but not entering plastic flow is a few percent above that of the metals not irradiated by the laser.

Post-damage sample analysis revealed no oxide formation in the irradiated zone.

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## ABBREVIATIONS AND SYMBOLS

$^{\circ}\text{C}$	Temperature, degrees centigrade
$\text{CO}_2$	Carbon dioxide
CW	Continuous wave
c	Heat capacity, $\text{J/gm}^{\circ}\text{K}$
$\text{cm}^2$	Square centimeter
D	Thermal diffusivity, $\text{cm}^2/\text{sec}$
J	Energy, joules
K	Thermal conductivity, $\text{J/sec cm}^{\circ}\text{K}$
KCl	Potassium chloride
kpsi	Pressure, thousand pounds per square inch
$T_m$	Melting point $^{\circ}\text{C}$
W	Power, watt
$\rho$	Density, $\text{gm/cm}^3$

## SECTION I

### INTRODUCTION

Laser heating of metal samples under stress is unique from the conventional techniques of resistance, induction, or hot fluid heating in at least two respects. First, the high brightness potential of the laser permits much greater heating rates than provided by other methods. The surface heating rates can be more than  $10^7$ ° C per second while the bulk thermal heating rates are limited only by the diffusivity of the material. A second feature of laser heating is its unidirectionality. This means that large temperature gradients can be established across samples. The large heating rates and thermal gradients induced by a laser in metals can cause metallurgical inertial effects that are even more complex than those occurring in conventional tensile experiments.

The mechanical strength of four structural metals is examined in this work during exposure to 10.6-micron laser radiation. Small flat metal specimens were heated rapidly by a continuous-wave (CW) laser beam while being subjected to a constant uniaxial tensile load. The objective of these experiments was to determine the dependence of the tensile yield stress on both the temperatures at which yielding occurs and the rate of heating or how rapidly the yield temperature is approached. Samples were initially uniaxially loaded at stresses ranging from 15 to 80 percent of their room temperature yield stresses. Heating rates obtained by the laser radiation ranged from 0.25 to 1.9 times a particular metal's melting temperature in degrees centigrade per second. The heating rates were varied by adjusting the power output of the laser.

## SECTION II

## DESCRIPTION OF THE EXPERIMENT

A tensile test sample is first loaded to some fraction of its room temperature yield stress, elongating it elastically. Then the laser begins to heat the sample causing a linear thermal expansion or an elongation proportional to the temperature increase of the test section of the sample. When the temperature is sufficiently high in the region being exposed by the laser, plastic flow begins.

Tensile yield is defined for these experiments as a 0.2-percent increase in length of the test section in excess of that elongation caused by simple thermal expansion. The temperature of yield is, therefore, defined as the temperature of the plastically extending region of the sample at the instant 0.2-percent offset is reached. Rapid heating continues of course, and the sample ruptures a very short time later.

The materials studied include 2024 aluminum, 6Al4V titanium, AZ31B magnesium, and 304 stainless steel. Table I contains the approximate composition and the thermal properties of these four alloys, the latter being average values between room temperature and the melt phase (ref. 1).

Specimens were fabricated such that loading occurred in the longitudinal grain direction. A flat, black, high-temperature paint, Plastic-Kote HP-11, was applied to the front surfaces of most samples in order to maximize the coupling of laser radiation into thermal energy in the sample. The low-intensity absorptivity, i.e.,  $5 \text{ w/cm}^2$ , for these painted surfaces at 10.6 microns was about 75 percent.

Two thermocouples were welded to the back surface of each sample as shown in figure 1: one in the center directly behind the point irradiated by the laser and another approximately 1.25 cm away on the test section to give an indication of the temperature profile developing in the sample with time. Chromel-alumel thermocouples were used on the aluminum and magnesium specimens, while platinum-rhodium junctions were necessary for the higher temperature rises in the titanium and stainless steel. A typical thermocouple junction was 0.010 cm in diameter. Sample rupture seldom occurred at a welded junction indicating that the small heat affected zone around the spot welds did not alter the experiment.

Table I

## MATERIAL PROPERTIES

Alloy	Heat Treatment	Composition % by Weight	Density gm/cm <sup>3</sup>	Thermal Conductivity (j/cm sec°K)	Heat Capacity (j/gm°K)	Thermal Diffusivity (cm <sup>2</sup> /sec)	Melting Point (°C)
2024-T3 Aluminum		4.9Cu, 1.8Mg, 0.9Mn, 0.5Fe, 0.5Si, 0.1Cr; Al	2.78	1.84	1.0	0.75	502
2024-T86 Aluminum Clad	Age Hardened from T3 to approx T86	4.9Cu, 1.8Mg, 0.9Mn, 0.5Fe, 0.5Si, 0.1Cr; Al	2.78	1.84	1.0	0.75	502
6Al4V Titanium	Annealed	6Al, 4V, 0.3Fe, 0.08C, 0.05N, 0.015H, 0.002; Ti	4.43	0.145	0.77	0.04	1600
304 Stainless Steel	Annealed	19Cr, 10Ni; 2Mn, 1Si, 0.08C; Fe	7.9	0.24	0.42	0.05	1400
AZ31B Magnesium	Hard rolled	3Al, 1Zn, 0.2Mn, 1.77Mg	1.77	0.96	1.04	0.52	607

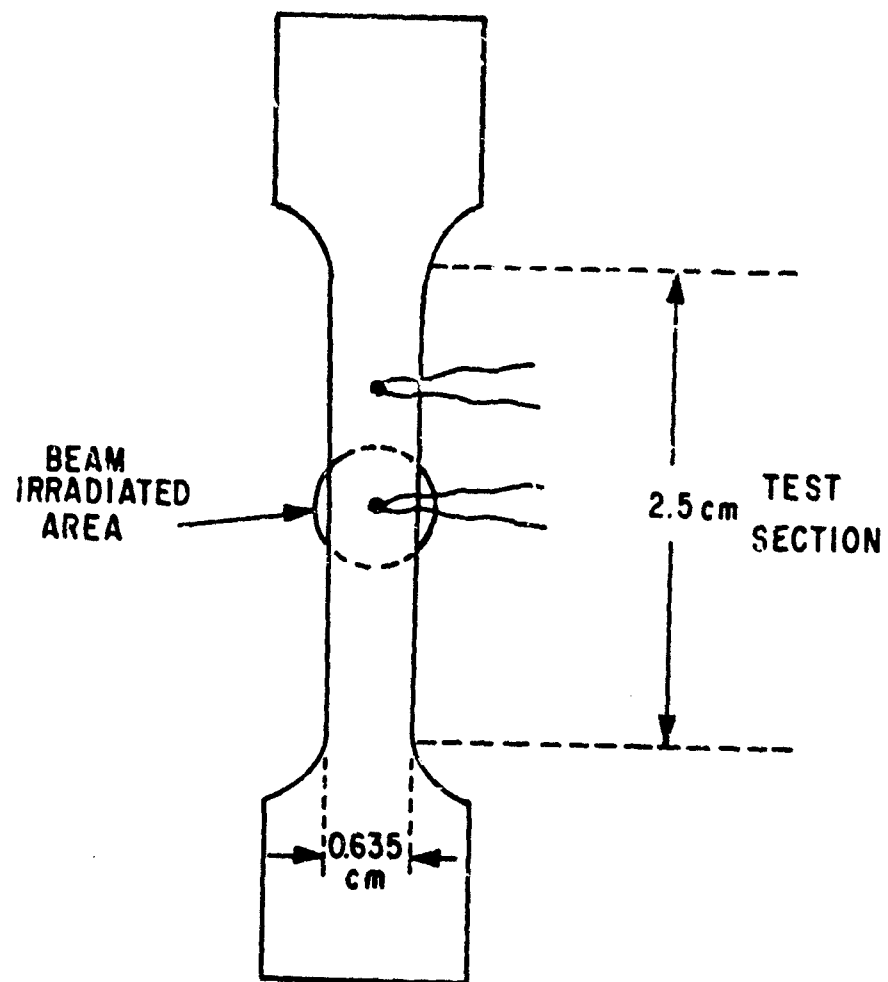


Figure 1. Sample Configuration (Back Surface)

Figure 2 shows the experimental apparatus. The Westinghouse Model C02200-CO<sub>2</sub> laser operates in either a continuous or pulsed mode. In the CW mode the power output is continuously adjustable from about 50 to 190 watts. The beam passes first through a 2-inch diameter KCl window with the reflected component directed into a CRL 201 thermopile power meter permitting continuous power measurement throughout an experiment. A CRL 213 power meter measured the total beam power arriving at the sample location for calibration. The meter was removed during the tests. The beam was controlled by a copper mirror shutter with a timing circuit that permitted the selection of a precise irradiation time interval. The total time required to open or close the shutter was about 0.05 second after receiving the signal from the timing circuit.

The beam then passed through an antireflection coated 2-inch-diameter germanium lens that focused it to the desired spot size on the test section of the tensile sample. Burn impressions obtained by exposing plexiglass to the laser beam at the location of the sample not only verified beam alignment before each tensile test but also provided information about the size of the irradiated area and the spatial intensity profile. The beam from the Westinghouse laser contains several hot spots whose intensities were up to twice the average. The average intensity was obtained by dividing the total beam power at the sample location measured with a thermopile by the area of a burn impression in plexiglass. All of the intensity values quoted for these tests are average intensities ranging from 80 to 223 w/cm<sup>2</sup>.

The test samples were loaded with an MTS model 483.01 closed-loop, servo-hydraulic materials test system with a 20-kips rating. The MTS system incorporates a Honeywell 540 XYY recorder that plotted the load cell and extensometer outputs versus time. An INSTRON Model G-51-11 strain-gage extensometer with a 1-inch gage length measured the sample elongation. This extensometer has a linearity of 0.25 percent over the range of zero to 0.1 inch of elongation. The combined load cell and extensometer are accurate to within 0.5 percent, while the time plotted on the abscissa has  $\pm 1$  percent accuracy. Signals from the shutter, the power meters, and both thermocouples were amplified with CEC 1-165 DC amplifiers and recorded on a CEC 5-124A oscillograph.

For each kind of metal, two measurements were performed to provide some background for the actual laser-heating tensile tests. First, a room yield curve was generated by loading a sample until failure at room temperature. This established room-temperature yield for each metal. Second, to obtain an estimate

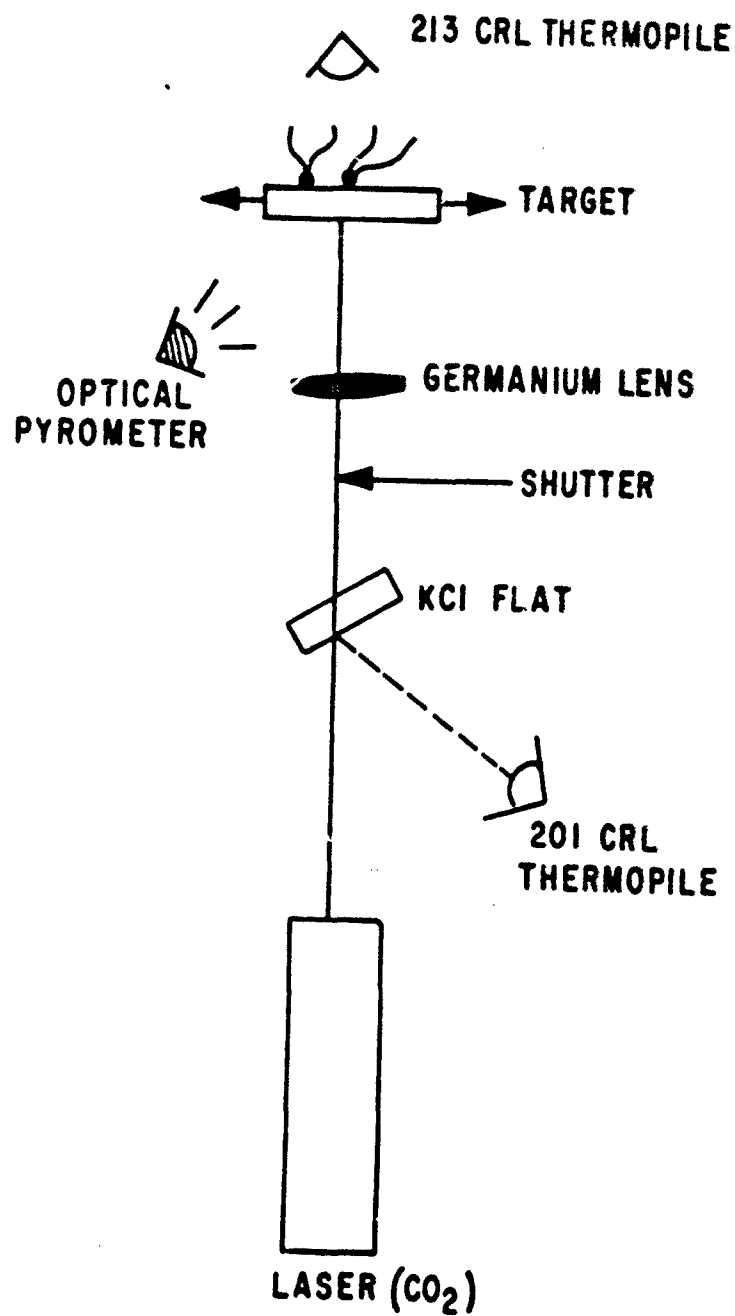


Figure 2. Experimental Apparatus

the sample elongation due only to thermal expansion, samples of each metal were heated by the laser in an unstressed condition and their elongation with time measured by the extensometer.

After the room-temperature yield stress and the thermal expansion caused by laser heating were determined, a series of samples of each metal was tested by first loading them to some fraction of their yield strength and then irradiating them with the laser. The time at which yield occurs was determined from the elongation versus time output of the extensometer after subtracting the elongation caused by thermal expansion. This "time of yield" was then correlated with the thermocouple outputs to obtain the average temperature of the test section at which yield occurred. This is the "yield temperature."

Figure 3 shows an example of the strain and temperature history for a 0.041-cm-thick stainless steel sample subjected to rapid laser heating. The constant initial load in this case was 23 kpsi. The solid line is the extensometer strain, with its initial linear portion caused by thermal expansion. As plastic flow ensues, the strain rate increases and the intersection with the 0.2 percent offset (dashed line) occurs at 0.95 second. The sample temperature at this temporal point is 790°C from figure 3.

Figure 4 shows the back center thermal response of a 0.079-cm-thick titanium sample preloaded to 77 kpsi. The coupling of 10.6-micron laser radiation with the painted surface is nearly constant at 75 percent. The observed decrease in the slope of the thermal response in figure 4 is mainly because of conduction losses toward the sample ends (see appendix). From the extensometer data, a 0.2-percent offset time of 0.74 second is deduced. In figure 4 this corresponds to a back surface temperature of 520°C.

Figures 5 and 6 show the tensile test specimens following irradiation. Post-damage analysis included X-ray scans for surface oxide formation. However, none was found. This was not surprising in view of the relatively low maximum surface temperatures reached during testing.



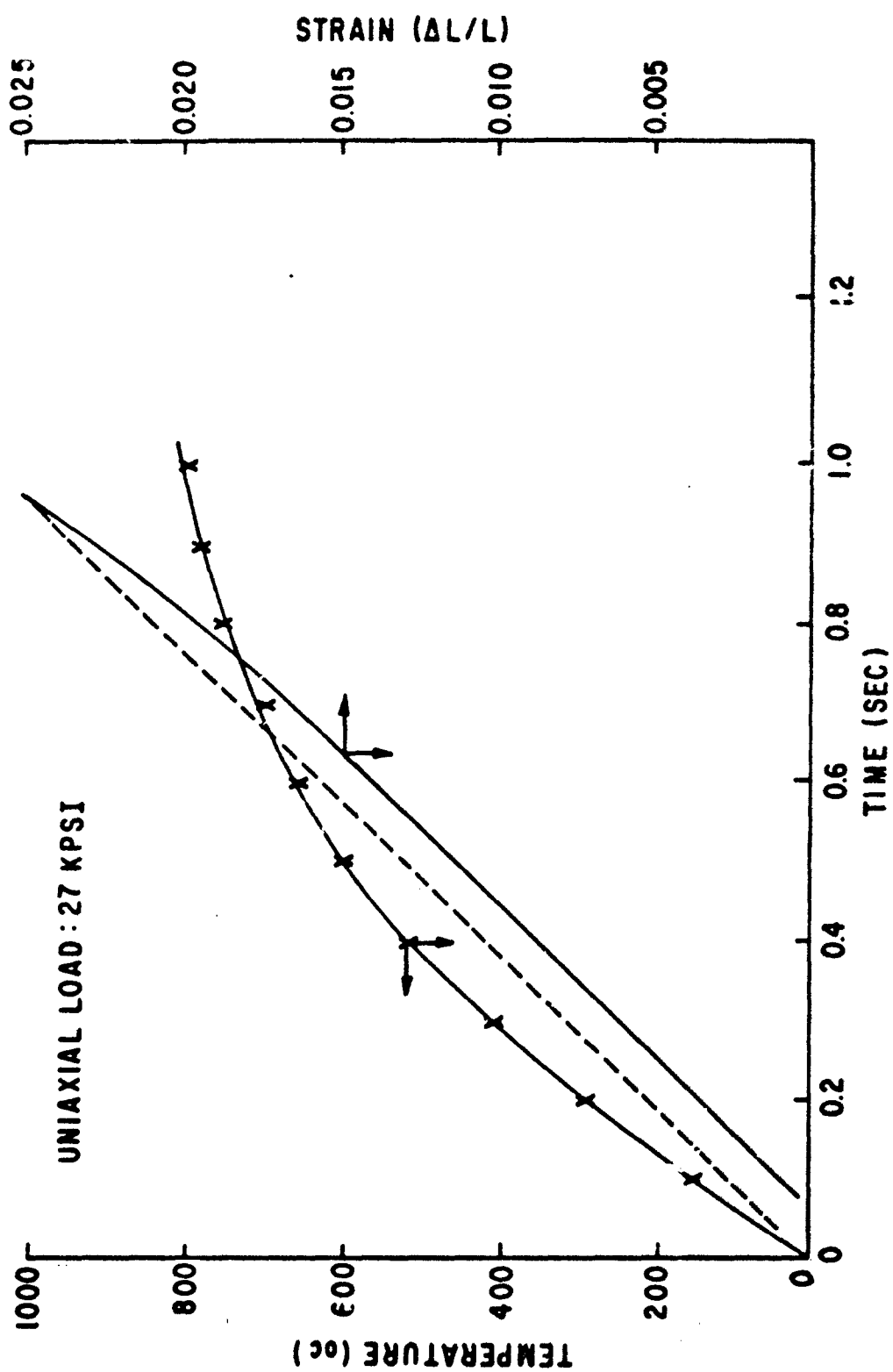


Figure 3. Strain and Temperature History for 0.041 cm Thick Stainless Steel

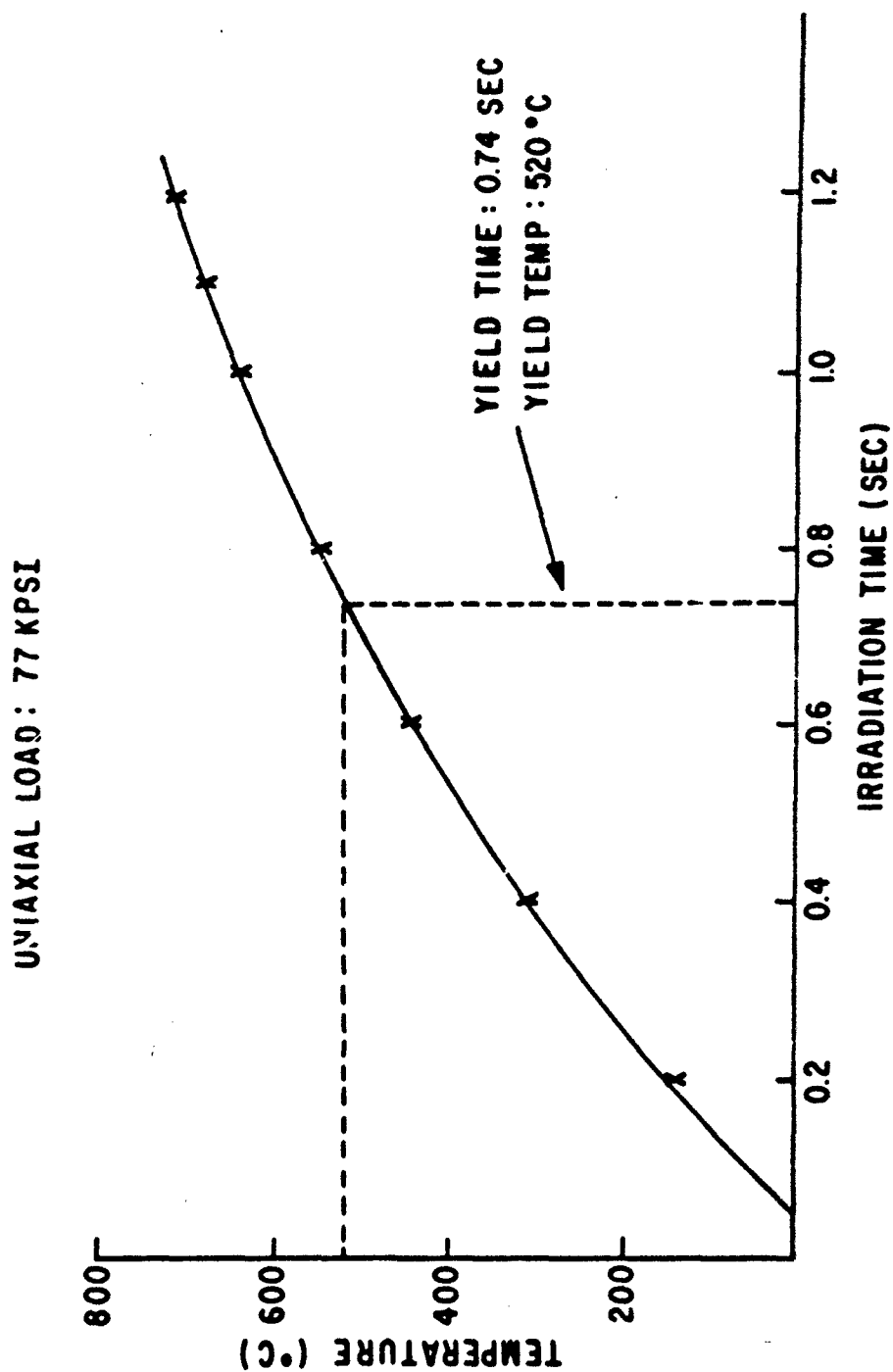


Figure 4. Back Surface Thermal Response of 0.079 cm Titanium

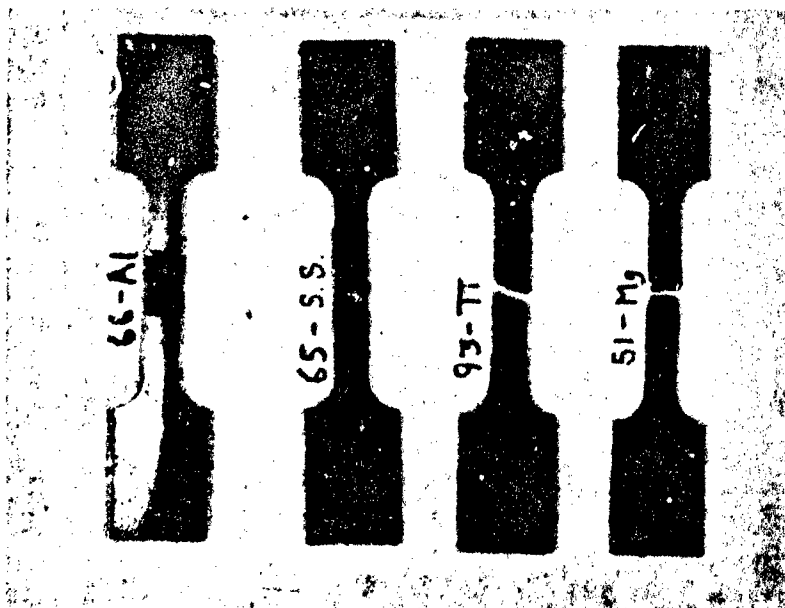


Figure 5. Four Metal Specimens Irradiated by  
Laser While Under Uniaxial Stress  
(7/10 Actual Size)

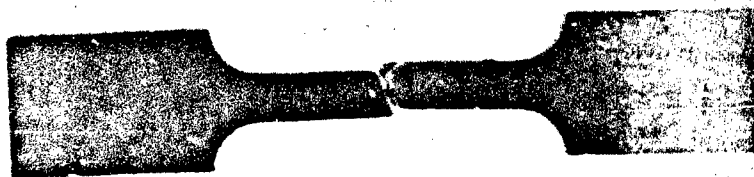


Figure 6. Laser-Induced Rupture in  
Titanium (6Al4V) Under Uniaxial Stress

## SECTION III

## RESULTS

## 1. MAGNESIUM, AZ-31B

Figure 7 shows sample yield temperature versus applied stress for magnesium AZ-31B. The room temperature yield was found to be about 28 kpsi. The laser-induced heating rates of these samples varied from 700°C/sec to 1140°C/sec. All magnesium specimens were painted on the front surface as the bare metal absorbs only about 5 percent of the incoming 10.6-micron radiation.

Long-time heating yield data are also shown in figure 7. For loads from 3 to 15 kpsi, the laser-heated samples yield at temperatures of 75 to 110°C above their long heat counterparts. Because of the relatively small number of magnesium samples tested, no meaningful heating rate versus yield temperature data were obtained.

Figure 8 shows the absorbed energy density on the 0.043-cm samples needed to induce yield for a given initial stress. An absorptivity of 80 percent is assumed, and the absorbed energy density is obtained by multiplying the product of absorptivity and beam intensity by the sample yield time. For comparison, the absorbed energy density required to melt this thickness of magnesium is about 47 J/cm<sup>2</sup>.

In conclusion, fast laser-induced heating of magnesium AZ-31B results in higher temperatures than conventional (long heat) specimens, reflecting an inertial property of the material's elastic strength to sudden temperature changes.

## 2. STAINLESS STEEL, 304

Two thicknesses of 304 stainless steel alloy were tested to allow correlation of the heating rate and yield temperature. Figure 9 shows stress versus yield temperature for the two thicknesses. These rapidly heated samples were subjected to constant stresses ranging from 25 to 85 percent of the measured room temperature yield stress value of  $40.8 \pm 2.4$  kpsi. The average heating rate for the five 0.081-cm-thick samples in figure 9, as recorded by the back center thermocouple, was  $340 \pm 95^\circ\text{C}$  per second. The error shown here is rms deviation. The

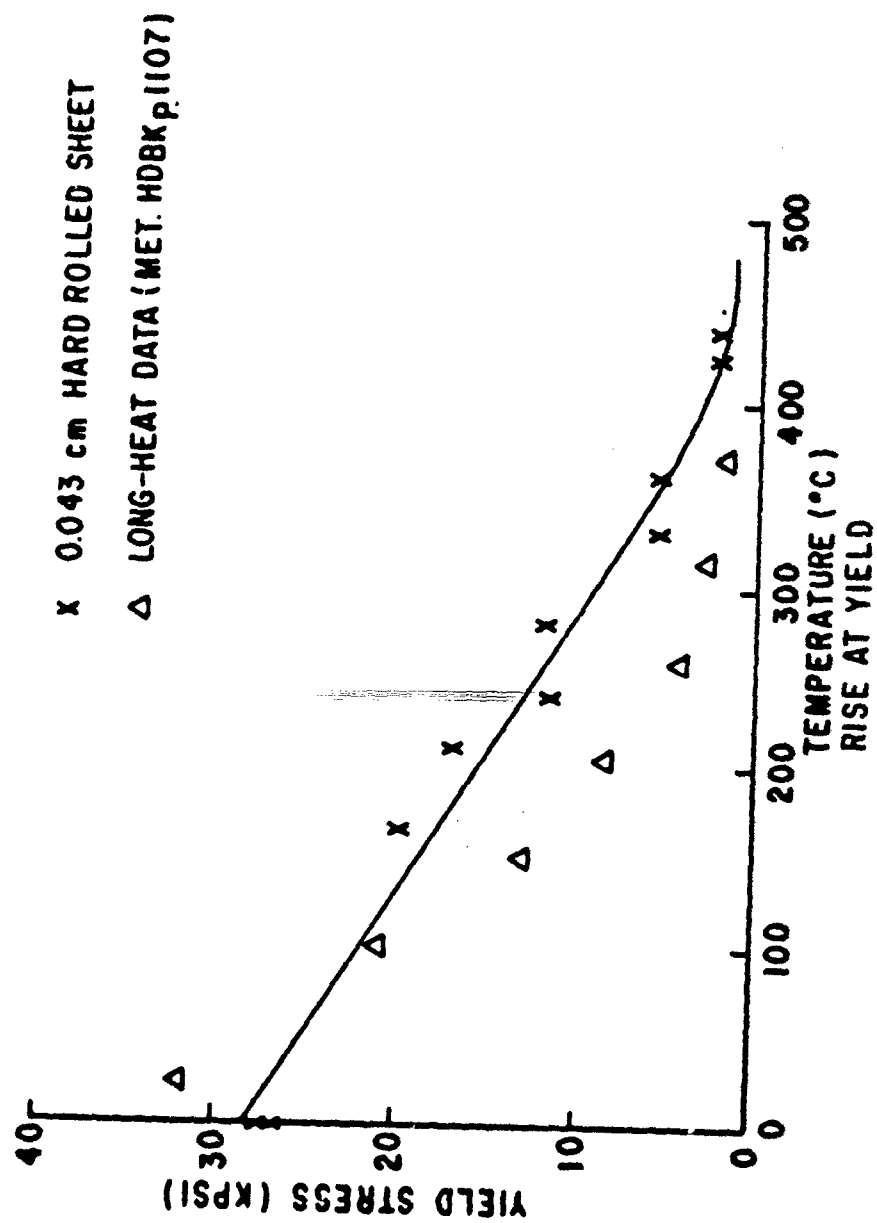


Figure 7. Yielding of Magnesium AE-31B

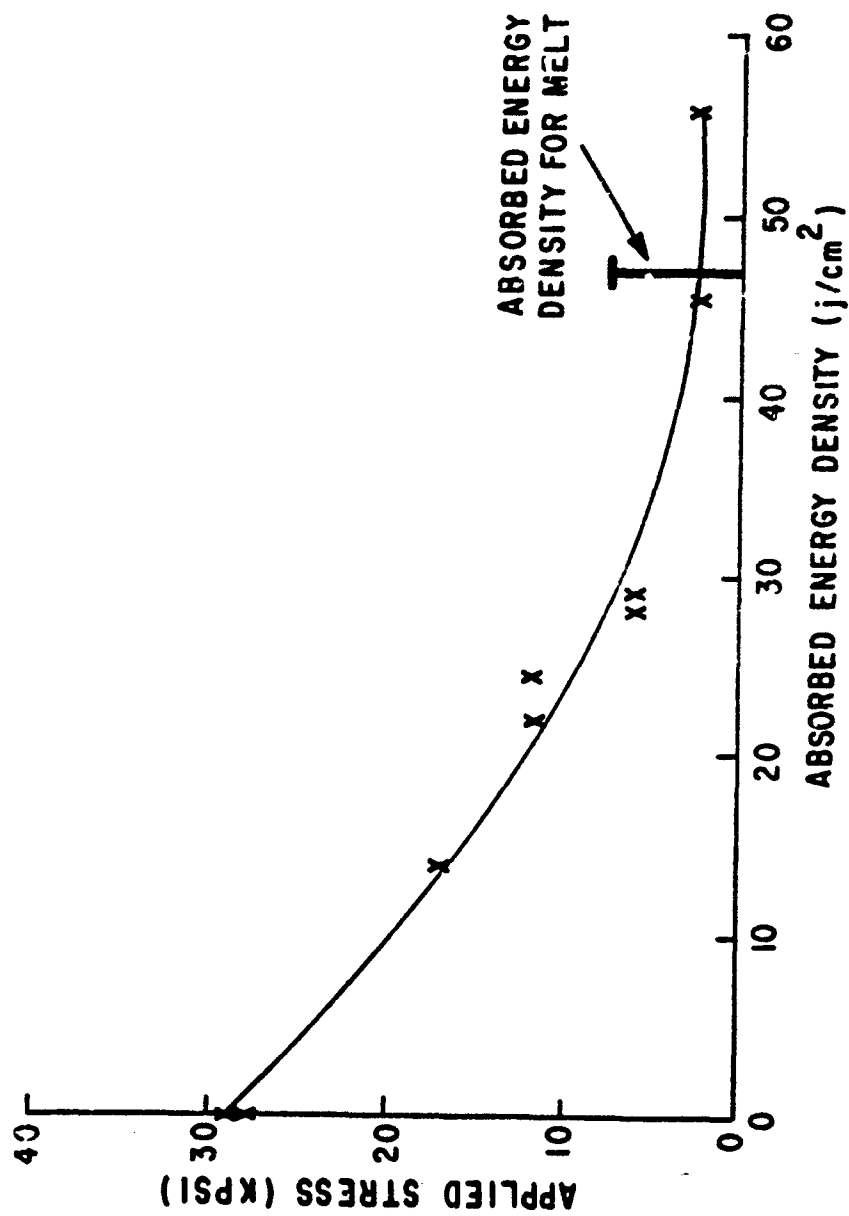


Figure 8. Absorbed Energy Density for Yielding of Magnesium AZ-31B

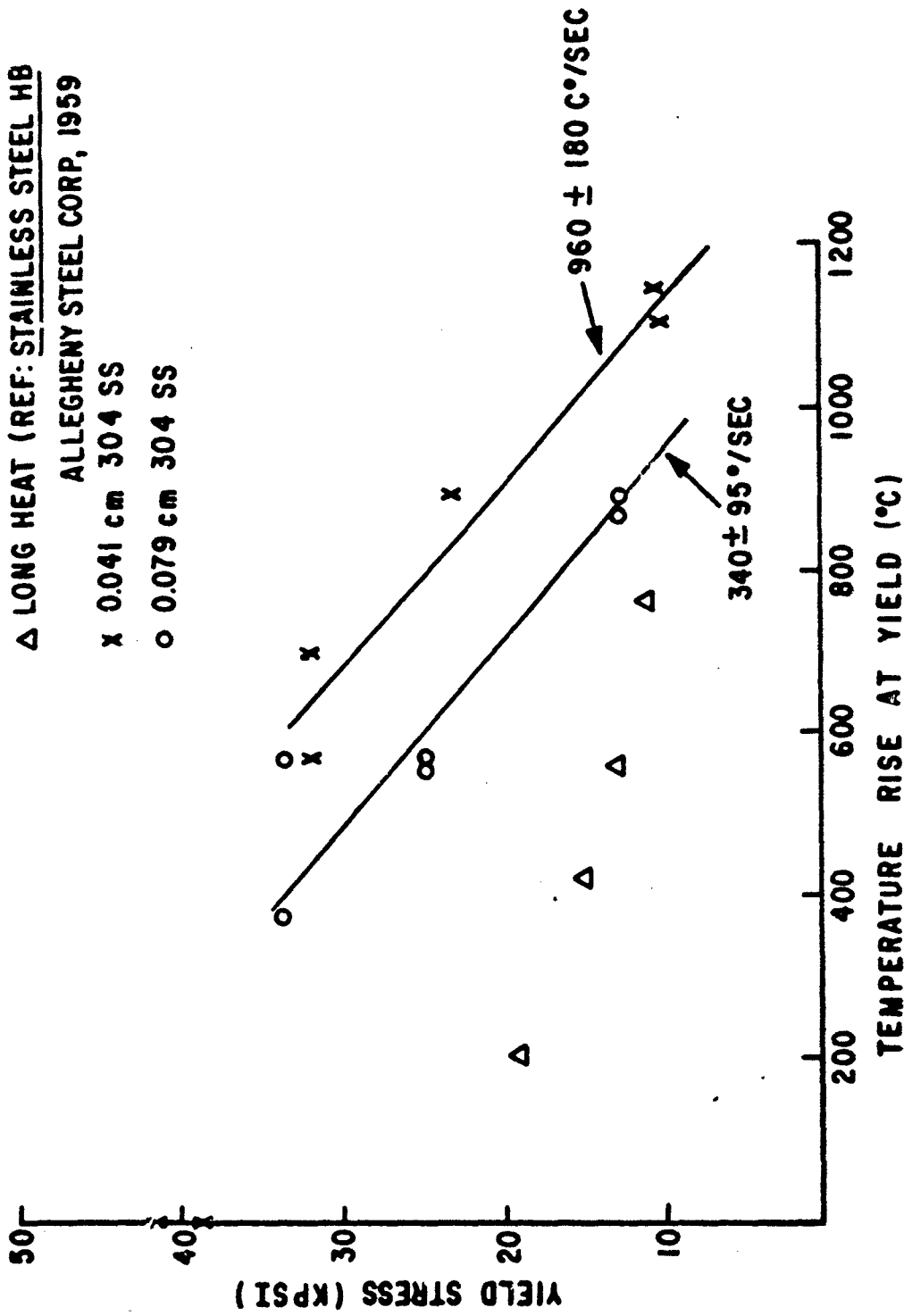


Figure 9. Yielding of Stainless Steel 304

corresponding heating rate of the thinner 0.041-cm-thick samples was  $960 \pm 180^\circ\text{C}$  per second. The melt temperature  $T_m$  of this stainless steel alloy is  $1400^\circ\text{C}$ , so our rates can be written  $0.24 T_m/\text{sec}$  and  $0.68 T_m/\text{sec}$ , respectively.

The best linear fit to the two sets of data in figure 9 shows that the average yield temperature increases with increasing heating rate. When loaded to approximately 30 percent of room temperature yield, the lower heating rate samples yielded at a temperature rise of  $900^\circ\text{C}$  (yield criterion is 0.2-percent offset), while at the higher heating rates the temperature rise at yield was about  $1080^\circ\text{C}$ . These temperatures correspond to 64 and 77 percent of the melting temperature, respectively.

Two unpainted 0.041-cm stainless steel 304 samples were irradiated under loads of about 63 percent of room temperature yield. Because of the relatively low-measured coupling constant with the 10.6-micron radiation (0.15), sample yield did not occur. Table II summarizes the two unpainted stainless experiments. Columns one and two show the preload and room temperature yield stresses, respectively. Column three gives the absorbed beam intensity. Columns four and five give the irradiation time and the maximum back-surface temperature achieved. The final column shows the measured yield strength of the two specimens after cooling to ambient temperature. The first point to note is the increase in strength of this alloy when laser heated to about one-half of its melting point at a rate of about  $110^\circ\text{C}/\text{sec}$ . Annealing of 304 stainless steel is normally accomplished by raising its temperature quickly to about  $1000^\circ\text{C}$ , holding for 5 to 6 minutes, and then quenching rapidly. This produces a fully annealed specimen. Although chromium-nickel grades of steel such as 304 cannot be hardened by conventional heat treatment, a hardening is observed here for laser heating.

### 3. TITANIUM 6A24V

High heating rate laser tensile tests were performed on painted and unpainted 6A24V titanium, which were 0.043 and 0.079 cm in thickness. The measured coupling constants with 10.6-micron radiation were typically 25 and 75 percent for unpainted and painted titanium, respectively. Average beam intensities ranged from 110 to  $220 \text{ w}/\text{cm}^2$ . Sample loadings during this series varied from 14 to 84 percent of the observed room temperature yield stress of  $142.5 \pm 2.5 \text{ kpsi}$ . The laser-induced heating rates ranged from about 600 to nearly  $1000^\circ\text{C}/\text{sec}$ .



Table II

## UNPAINTED STAINLESS STEEL 304 RESULTS

Preload (kpsi)	Room Temp Yield Stress (kpsi)	Intensity Absorbed (w/cm <sup>2</sup> )	Irradiation Time (sec)	Maximum Temp Reached (C°)	Yield Stress After Heating
25.7	40.8 ± 2.4	29	6.3	720	48.8
25.7	40.8 ± 2.4	29	6.5	720	44.0

Figure 10 shows stress versus yield temperature for 6A24V titanium. These results do not indicate a marked dependence of yield temperature on heating rate. In fact, the thicker (0.079 cm) painted titanium has a lower average heating rate of  $615 \pm 235^\circ\text{C}$ , and apparently a slightly higher average yield temperature than its 0.043-cm painted counterpart. A partial explanation of this may be the relatively large temperature gradient established across titanium by the incident flux. The gradient across a laser irradiated sample of thickness  $x$  is approximately

$$\Delta T \approx \frac{\alpha I x}{2 K}$$

where  $\alpha I$  is the absorbed flux and  $K$  the thermal conductivity of the material. The predicted gradient for a 0.08-cm titanium sample under the experimental conditions is about  $50^\circ\text{C}$ , which is about 10 percent of observed yield temperatures.

The bars in figure 10 indicate long time heating data from The Metals Handbook (ref. 2). These stress versus yield curves lie very close to the 0.043-cm painted 6A24V data. Figure 11 shows the measured absorbed energy density required to cause 0.079-cm titanium to yield assuming absorptivities of 25 and 75 percent for unpainted and painted surfaces, respectively. Melting of this sample thickness requires an absorbed energy density of approximately  $430 \text{ J/cm}^2$ .

In conclusion, the yielding of 6A24V titanium under constant load is rather insensitive to heating rate. A sample preloaded to 25 percent of its room temperature yield strength will yield at about one-half its melting point or  $800^\circ\text{C}$ .

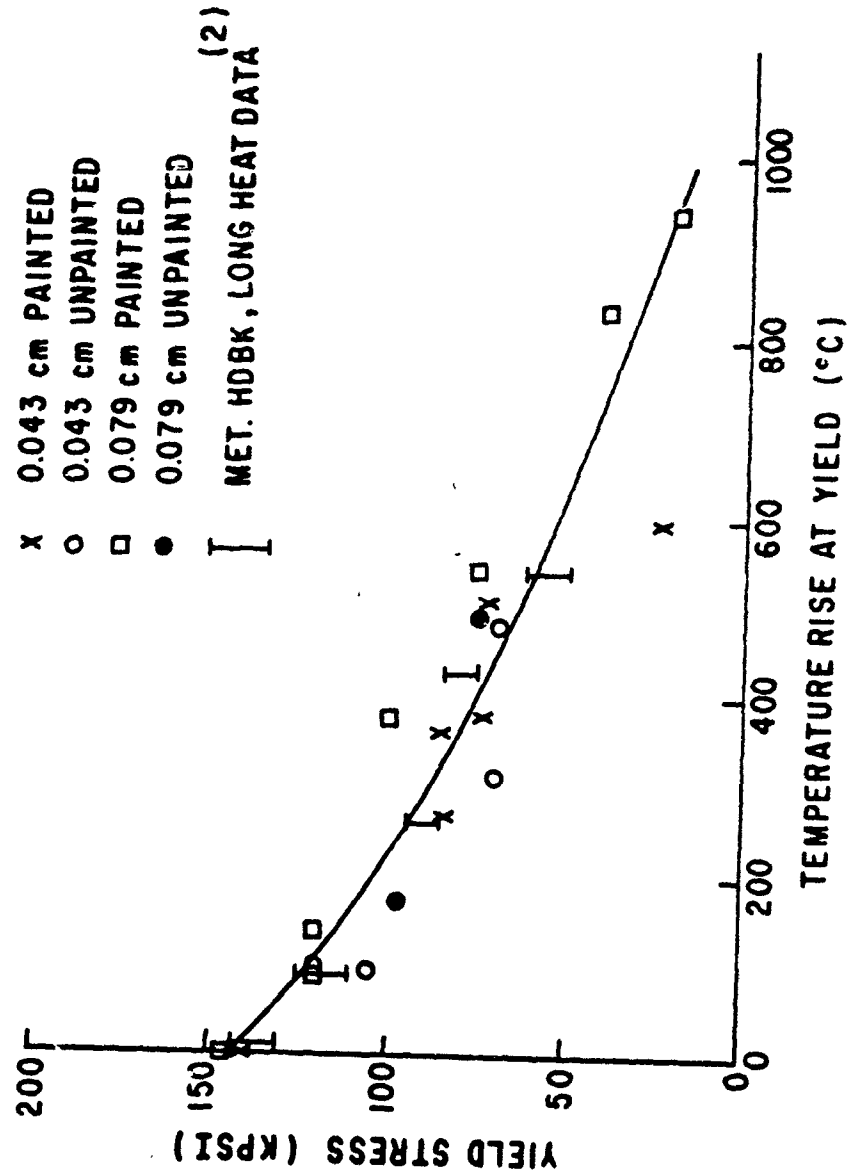


Figure 10. Yielding of Titanium alloy

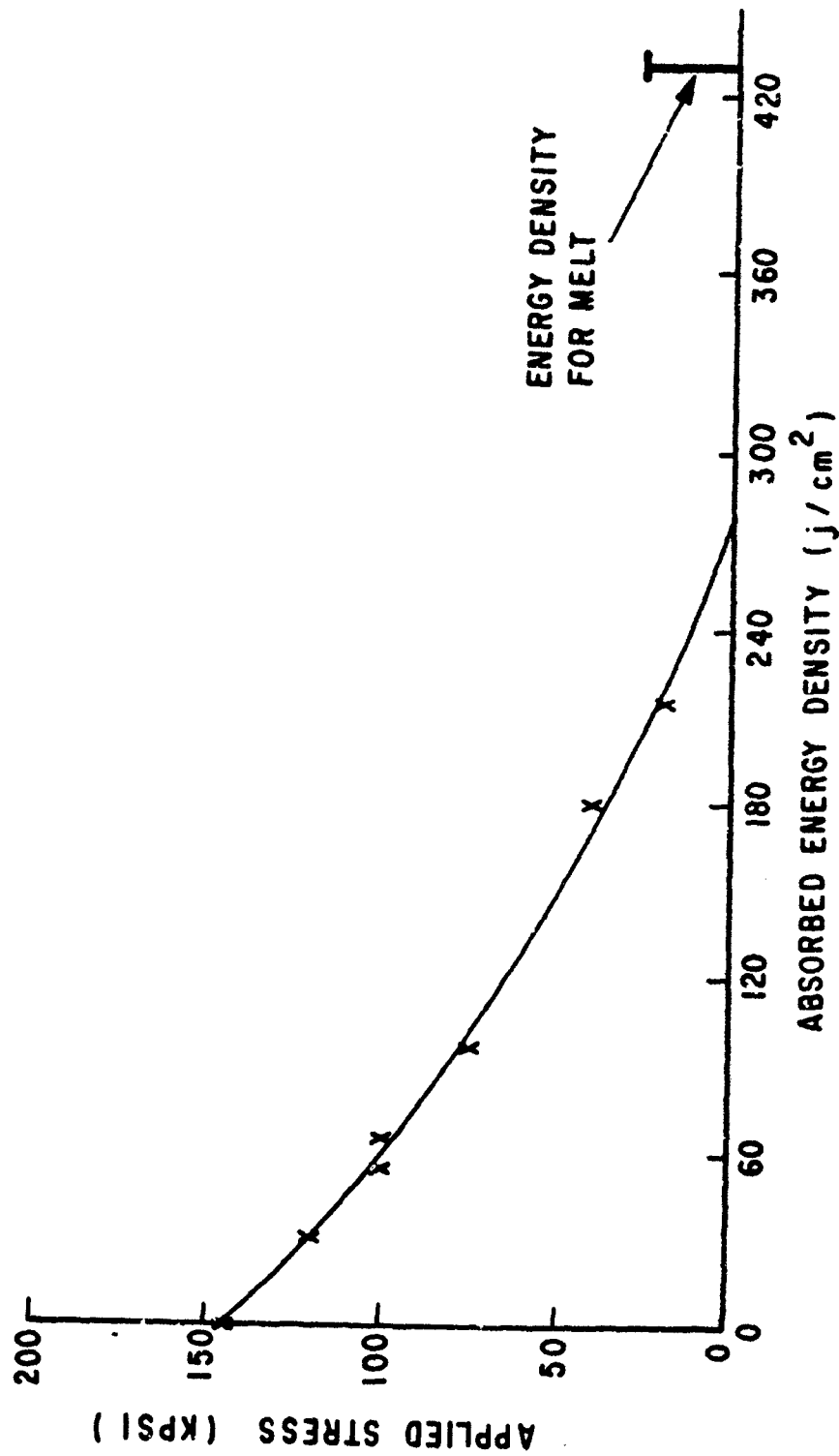


Figure 11. Absorbed Energy Density for Yielding of 0.079 cm Titanium 6Al4V

## 4. ALUMINUM 2024, T3 + T86

Samples of 2024 aluminum of heat treatments T3 and T86 were tested. Table 1 lists the properties of this aluminum alloy. Specimens were painted to increase the unpainted metal absorptivity of about 5 percent to approximately 75 percent.

Figure 12 compares the experimental yield stress versus yield temperature of long heat data without present laser irradiated samples for 2024 T86. This material showed a room temperature yield of  $68 \pm 2$  kpsi. The average laser heating rate of the six specimens tested was  $370 \pm 30^\circ\text{C/sec}$ , while the constant stress levels ranged from 20 to 85 percent of the room temperature yield values. Notice that the yield temperatures for rapid heating are about  $75^\circ\text{C}$  above their long heat counterparts for equal stresses.

High heating rate tensile tests were completed on several thicknesses of aluminum 2024 T3, ranging from 0.100 to 0.168 cm. The room temperature yield for this material was found to be  $41 \pm 1$  kpsi. Figure 13 summarizes stress versus yield temperature for the 0.100-cm-thick samples shown for comparative purposes are Simon's (ref. 4) rapid resistance heating data plus some long soak data in which specimens are first held unstressed at temperature for 1000 hours and then stressed to their yield point. The 1000-hour soak experiments yield at a considerably lower temperature.

Figure 14 gives yield stress versus sample yield temperature for 0.132-cm-thick Al 2024-T3. The average heating rate is  $174 \pm 40^\circ\text{C}$  per second. Although few samples were tested, the slope of the data seems to agree roughly with that of the 0.100-cm Al specimens of figure 13.

In summary, Al 2024 T3 samples loaded to 25 percent of room temperature yield and then heated rapidly (about  $250^\circ\text{C/sec}$ ) will yield at  $375^\circ\text{C}$ , which is about 75 percent of the melting temperature in degrees centigrade.

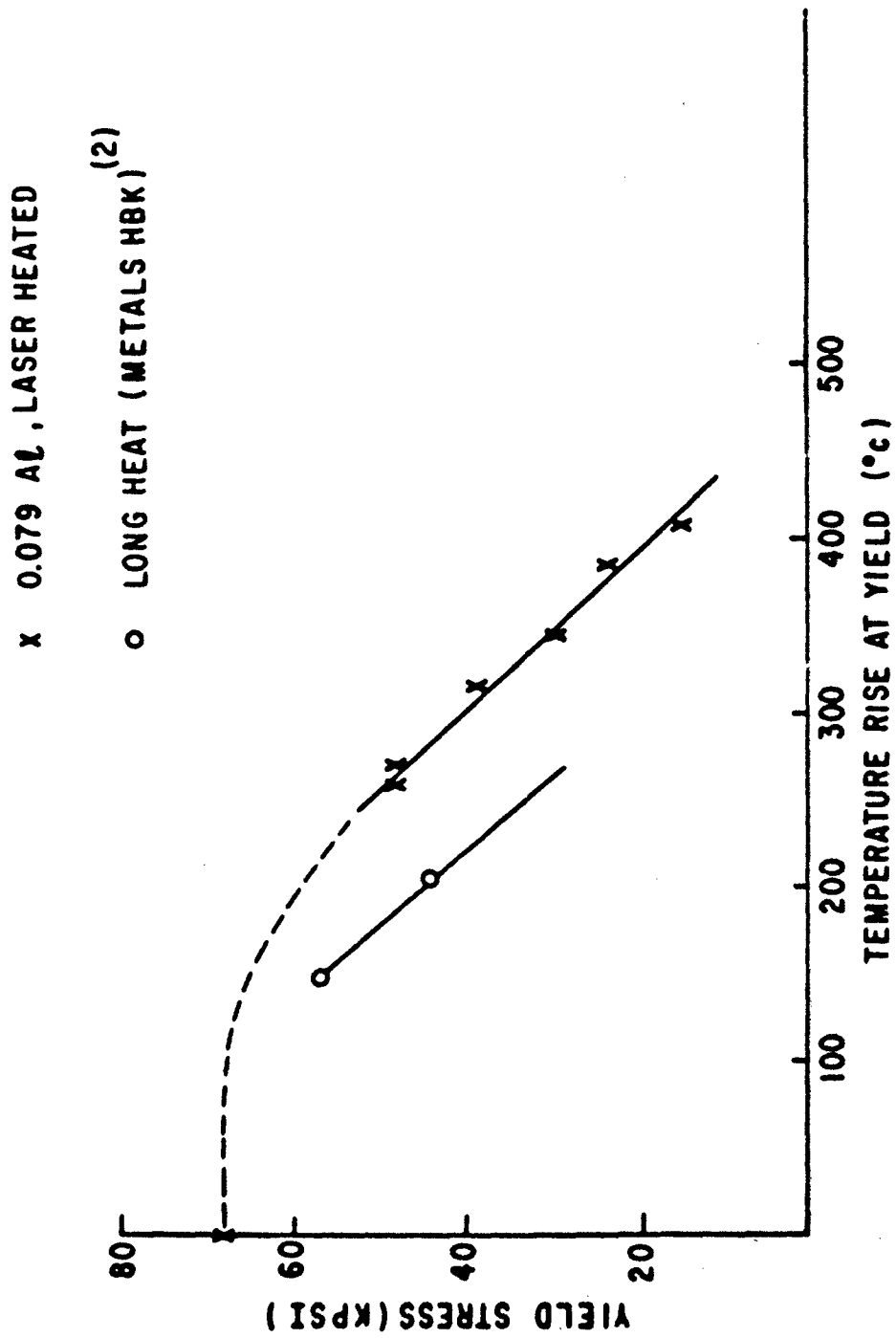


Figure 12. Yielding of Aluminum 2024 T86

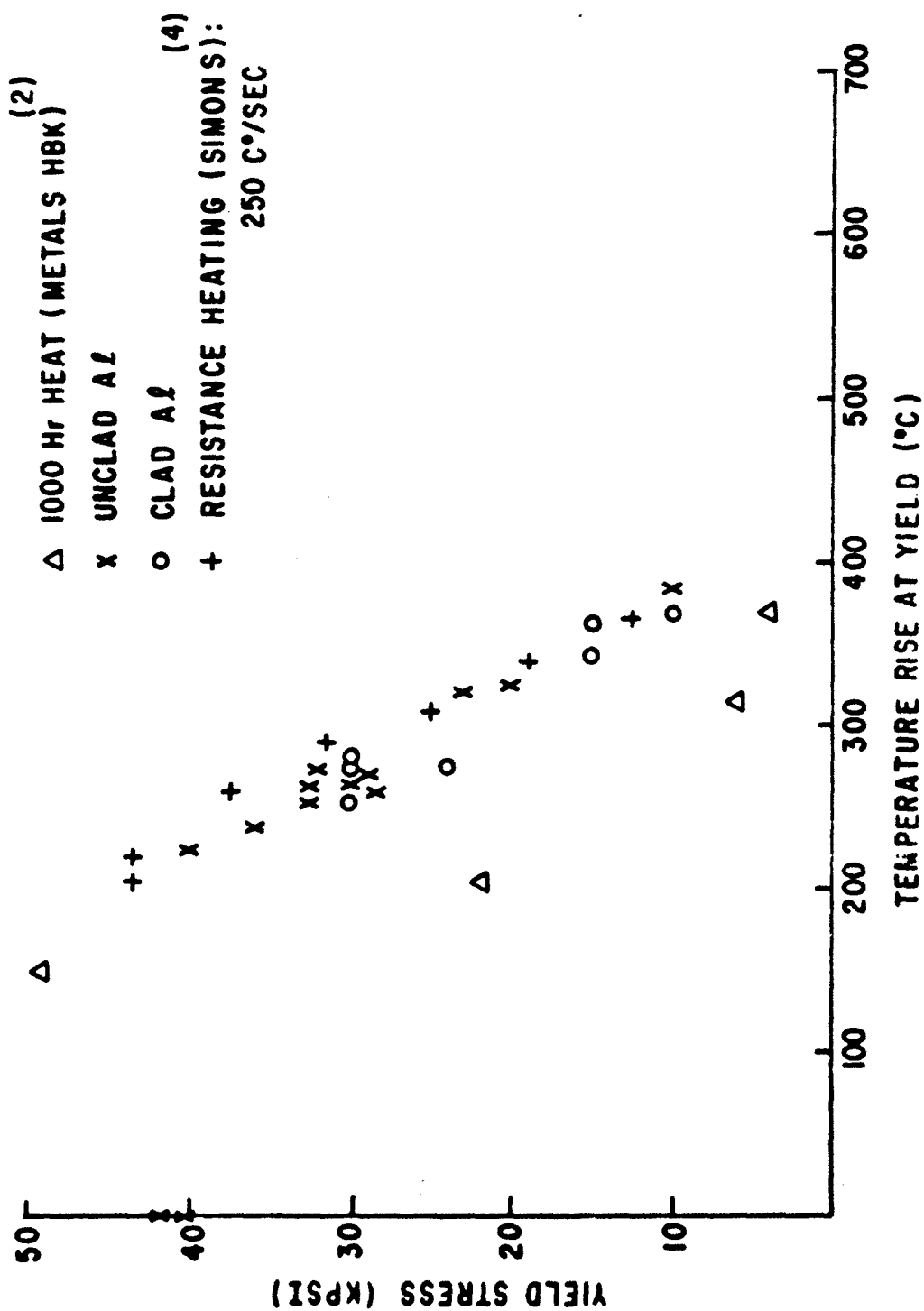


Figure 13. Yielding of 0.109 cm Aluminum 2024 T3

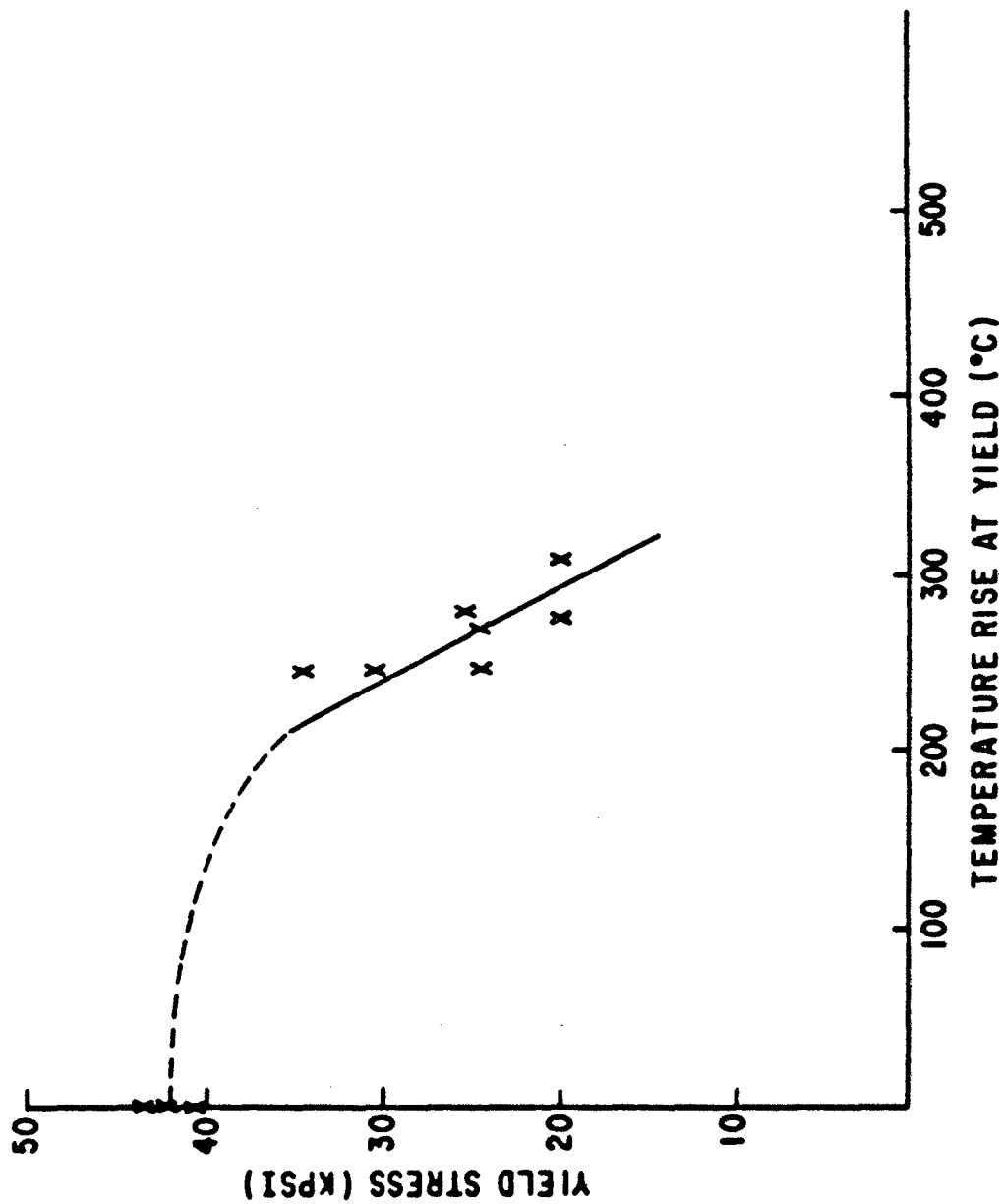


Figure 14. Yielding of 0.132 cm 2024 T3 Aluminum

## SECTION IV

## CONCLUSIONS

Four metals have been subjected to rapid heating via a 10.6-micron  $\text{CO}_2$  laser. All samples were under a constant uniaxial tensile load during laser irradiation. In general, the rupture of these samples occurs at temperatures higher than those recorded from conventional ultimate tensile strength tests. Furthermore, as the rate of heating increases, the yield temperature increases for a given constant stress. The static yield strength generally agreed with literature values. Residual strengths of laser irradiated samples that did not experience yield are sometimes several percent above similar virgin samples.

Table III summarizes the average yield temperatures (0.2-percent offset) recorded for our four metal specimens uniaxially loaded to 20 percent and 50 percent of their room temperature yield stresses ( $\sigma_y$ ). The final column lists the approximate melting temperature for each specimen.

Table III  
SUMMARY OF DATA

Alloy	$0.20\sigma_y$	$0.50\sigma_y$	$T_m (^{\circ}\text{C})$
Titanium (6A 4V)	900°C	580	1600
Stainless Steel (304)	1180	920	1400
Magnesium (AZ-31B)	350	250	607
Aluminum (2024 T86)	415	330	502
Aluminum (2024 T3)	390	320	502

Finally, further tensile testing is planned with a larger laser. This will permit incident beam intensities in the range 1 to 5 kilowatts/cm<sup>2</sup> with corresponding spot sizes in excess of one cm<sup>2</sup>. In this range any further uniqueness of laser heating of uniaxially loaded metals should be demonstrated.



## APPENDIX

TEMPERATURE DISTRIBUTION IN A LASER-HEATED  
TENSILE TEST SPECIMEN

The temperature distribution developing with time in a thin tensile specimen as it is being irradiated by a laser may be represented by a one-dimensional model. For such a model, a one-dimensional (x-direction) transient heat transfer solution is available from Carslaw and Jaeger (ref. 5), for absorption of energy over a finite depth, in a semitransparent material. This solution expresses  $T = f(x, t)$  for a semi-infinite solid with two expressions, one for the region,  $0 < x < l$ , where the heat deposited per unit volume per unit time is  $A_0$ , and another for the region,  $x > l$ , where no heat is deposited.

$$T = \frac{DA_0t}{K} \left[ 1 - 2i^2 \operatorname{erfc} \left( \frac{l-x}{2(Dt)^{1/2}} \right) - 2i^2 \operatorname{erfc} \left( \frac{l+x}{2(Dt)^{1/2}} \right) \right] \quad 0 < x < l \quad (1)$$

and

$$T = \frac{2DA_0t}{K} \left[ i^2 \operatorname{erfc} \left( \frac{x-l}{2(Dt)^{1/2}} \right) - i^2 \operatorname{erfc} \left( \frac{x+l}{2(Dt)^{1/2}} \right) \right] \quad x > l$$

where

$T$  is temperature rise ( $^{\circ}\text{C}$ )

$t$  is irradiation time (sec)

$D$  is thermal diffusivity ( $\text{cm}^2/\text{sec}$ )

$K$  is thermal conductivity (joules/sec cm  $^{\circ}\text{C}$ )

$l$  is depth to which energy is deposited (cm)

If the tensile test specimen is thin and its face irradiated by the beam is somewhat narrower than the beam diameter, conduction of heat away from the heated spot is essentially one-dimensional, i.e., along the sample length in both directions (fig. 15). Also if the incoming laser beam is assumed to be of even intensity,  $I$ , with a radius,  $i$ , then conduction of heat in the thin tensile test specimen of thickness,  $d$ , being heated on one face can be represented approximately by the above Carslaw and Jaeger solution with  $A_0$  replaced by  $\alpha I/d$  where  $\alpha$  is the surface absorption coefficient.

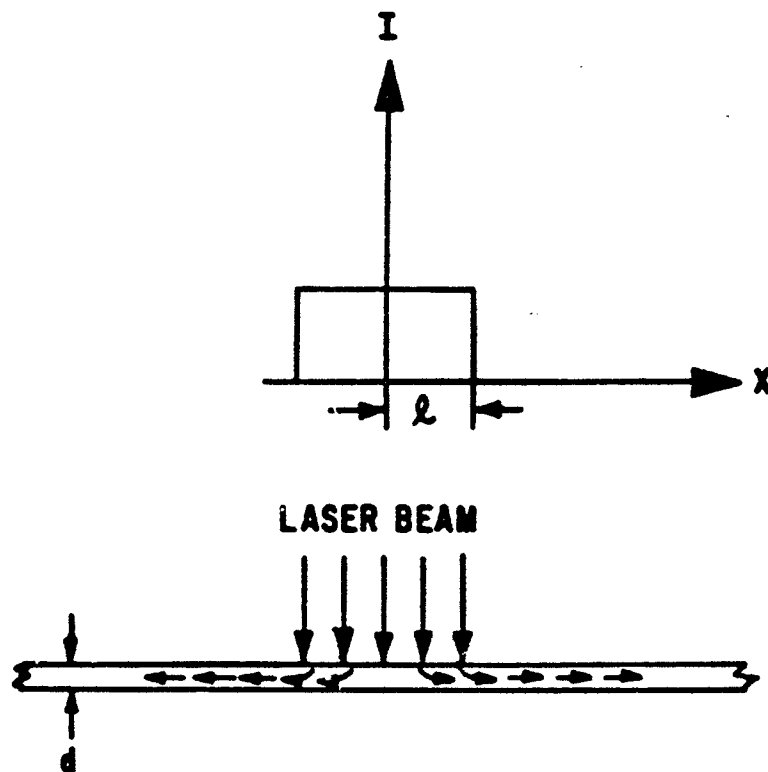


Figure 15. Edge View of Tensile Stress Specimen Showing the Intensity Profile of the Laser Beam and the Direction of Heat Flow

$$T = \frac{\alpha I l t}{dK} \left[ 1 - 2i^2 \operatorname{erfc} \left( \frac{l-x}{2(Dt)^{1/2}} \right) - 2i^2 \operatorname{erfc} \left( \frac{l+x}{2(Dt)^{1/2}} \right) \right] \quad 0 < x < l$$

$$T = \frac{2\alpha I D t}{dK} \left[ i^2 \operatorname{erfc} \left( \frac{x-l}{2(Dt)^{1/2}} \right) - i^2 \operatorname{erfc} \left( \frac{x+l}{2(Dt)^{1/2}} \right) \right] \quad x > l \quad (2)$$

The temperature given by the first expression in the region  $0 < x < l$  is really an average temperature over the sample thickness,  $d$ , while at larger distances,  $x$ , away from the irradiated area the second temperature will be more exact. For the samples thicknesses and heating rates studied here, front-to-rear surface temperature differences are in the order of 1 to 2°C for the high-conductivity metals such as aluminum and 10 to 20°C for the low-conductivity metals such as stainless steel.

Looking at equation (2) for  $x < l$  the  $\alpha I D t / dK$  term is just the expression for the one-dimensional heating of an evenly irradiated thin flat plate while the terms contained in the brackets can be regarded as a "correction term"

adjusting the temperature of the irradiated section for conduction lost toward the sample ends.

Assistance in evaluating  $T = f(x,t)$  is provided by the following error function definition and relationships.

$$\operatorname{erf} y = \frac{2}{\sqrt{\pi}} \int_0^y e^{-y'^2} dy' \quad (3)$$

$$\operatorname{erfc} y = 1 - \operatorname{erf} y \quad (4)$$

$$2n i^n \operatorname{erfc} y = i^{n-2} \operatorname{erfc} y - 2y i^{n-1} \operatorname{erfc} y \quad (5)$$

$$i^0 \operatorname{erfc} y = \operatorname{erfc} y \quad (6)$$

$$i \operatorname{erfc} y = \frac{1}{\sqrt{\pi}} e^{-y^2} - y \operatorname{erfc} y \quad (7)$$

Therefore

$$i^2 \operatorname{erfc} y = \frac{1}{4} \left[ (1 + 2y^2) \operatorname{erfc} y - \frac{2}{\sqrt{\pi}} y e^{-y^2} \right] \quad (8)$$

A computer program has been developed for a least difference fit to the experimental temperature rise data from back center and distant thermocouples with equations (2), finding an effective surface absorption coefficient for the incoming laser radiation.

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	ROLE	WT	ROLE	WT	ROLE	WT
Rapid laser heating of stressed metals Uniaxially loaded metals CO <sub>2</sub> laser Tensile yield Plastic creep						
Continuation of Item 13:						
Titanium 6Al4V yield temperature has very little dependence on heating rate. Yield data on 2024 aluminum under rapid laser heating agrees well with that from rapid electrical resistance heating. Both yield temperatures lie 50 to 100°C above the long soak data.						
The residual strength of samples irradiated but not entering plastic flow is a few percent above that of the metals not irradiated by the laser.						
Post-damage sample analysis revealed no oxide formation in the irradiated zone.						

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